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DEVELOPMENT OF NON-DESTRUCTIVE TESTING METHODS
FOR PROVING AND RE-TESTING LOW PRESSURE,
FIBRE REINFORCED PLASTIC HIGHWAY TANKERS

Prepared for

Transportation Development Center
Policy and Coordination Group
Transport Canada

DEPARTMENT OF MECHANICAL ENGINEERING

FACULTY OF ENGINEERING AND COMPUTER SCIENCE

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by

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16. Abstract

Fiber reinforced plastic (FRP) road tankers have characteristics which give them advantages over their metallic counterparts in the transportation of corrosive liquids and wastes. Reliable methods of non-destructive testing are needed to assure their safe operation over a long service life which includes pressure loading. The use of acoustic emission (AE) detection and analysis can be fast and inexpensive compared to other methods. Available AE procedures are found to be inapplicable to FRP road tankers with Balsa wood core (BWC); their use leads to false rejections. A new procedure using the trend in AE activity during repeated pressure loading of such road tankers has been developed. A simple way of measuring the AE Activity trend has been found, and criteria for making acceptance/rejection decisions have been proposed. These are based on experiments including 25 tanker tests, 8 of which are conducted up to the burst pressure. A recommended practice has been proposed for FRP/BWC road tankers. The scope of the practice might be extended to other FRP structures.

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16. Résumé

Les camions-citernes en plastique renforcé de fibres de verre (PRF) ont des qualités qui leur donnent des avantages sur ceux qui sont faits de métaux dans le transport de produits et de déchets liquides corrosifs. Des méthodes fiables d'essais non-destructifs sont nécessaires pour assurer le fonctionnement sécuritaire des citernes pendant de longues années de service, ce qui inclus également le chargement sous pression. La surveillance et l'analyse par détection d'émission acoustique (EA) peuvent s'avérer rapides et peu onéreuses contrairement à d'autres méthodes. Par contre, des essais sur des camions-citernes en PRF avec âmes de bois de balsa (ABB) ont montré que les procédés de contrôle par EA présentement disponibles sont inapplicables et mènent à des rejets. Un nouveau procédé qui se base sur la tendance de l'activité d'EA lors de pressions répétées a été développé pour de telles citernes. Une façon simple d'évaluer cette tendance a été trouvée, et des critères de conformité ont été proposés. Ces critères sont fondés sur 25 essais effectués sur des citernes, dont huit jusqu'à rupture. Une procédure recommandée a été proposée pour les camions-citernes en PRF/ABB. Le champ d'application de cette procédure pourrait s'étendre à d'autres structures en PRF.

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Plastique renforcé de fibres, camions-citernes, contenants sous pression en composite, essai non-destructif, essai par émission acoustique.	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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SUMMARY

The use of fiberglass reinforced plastic (FRP) in the transportation of corrosive and waste liquids is appealing to an increasing number of highway tanker operators. Because of the serious consequences of a failure of this type of equipment, appropriate methods of design as well as reliable quality control techniques are required. The present project was undertaken to address the latter concern.

Acoustic Emission (AE) monitoring of pressurized FRP vessels presents several advantages in non-destructive acceptance testing. It can be done quickly and inexpensively. However, testing on FRP tankers with Balsa wood cores (BWC), indicated that available AE test procedures would result in false rejection of these tankers.

A new method of AE testing FRP/BWC tankers was developed over 39 months by observing AE activity trends upon repeated pressurization of these structures. Twenty-five tanker tests were conducted; eight of these were run to the bursting pressure. A simple method of measuring AE activity trend was developed, and unambiguous acceptance/rejection criteria were proposed. These criteria, while in keeping with the general philosophy of previous methods, give quantitative limits which were not previously available. The new method is less dependent on the judgement and experience of testing personnel; the method is considered much less affected by the wide variations in test results caused by changes in instrumentation, set-up, and construction details and fabrication methods used for FRP/BWC structures.

The project has permitted us to prepare and propose a new recommended practice for AE testing of FRP/BWC road tankers. The document has been circulated among members of the Committee on Acoustic Emission from Reinforced Plastics, which is now affiliated with the American Society for Nondestructive Testing.

Because the new practice is based on the empirical results obtain during the present project, it is felt that its scope should be restricted to FRP/BWC pressure vessels for the present. The authors think that it may have much broader applicability, but it is necessary to perform appropriate studies before the scope is extended.

SOMMAIRE

L'utilisation de plastiques renforcés de fibres de verre (PRF) attire l'attention des opérateurs de citernes routières pour le transport de produits et déchets liquides corrosifs. Étant donné les consequences graves de la rupture de tels contenants, des méthodes de design et de contrôle pour l'assurance de qualité sont requises. Le but de ce projet est le développement d'une telle méthode de contrôle.

La surveillance par détection d'émission acoustique (EA) des contenants de PRF sous pression offre plusieurs avantages dans le contrôle non-destructif. Elle est relativement rapide et peu onéreuse. Par contre, des tests de citernes routières de PRF avec âme de bois balsa (ABB) ont montrés que les procédures de contrôle par EA présentement disponibles mèneraient à des rejets erronés.

Une nouvelle méthode de surveillance par EA de citernes routières de PRF/ABB a été développée sur une période de 39 mois par l'observation de tendances dans l'activité d'EA lors de pressurisations répétées. Vingt-cinq tests de citernes, dont huit jusqu'à rupture, ont été effectués. Une manière simple de mesurer la tendance de l'activité d'EA a été élaborée, et des critères de conformité sans ambiguïtés ont été proposés. Ces critères, tout en respectant la philosophie générale des méthodes antérieures, définissent des normes quantitatives jusqu'ici inexistantes. La nouvelle méthode est moins subordonnée au jugement et à l'expérience des contrôleurs; elle est aussi moins biaisée par les grands écarts dans les résultats qui sont attribuables à des variations dans

l'instrumentation, les préparatifs expérimentaux, et les détails de construction et méthodes de fabrication des structures de PRF/ABB.

Le projet nous a permis d'élaborer et de proposer une nouvelle procédure pour contrôle par EA des citernes routières de PRF/ABB. Le document a été presenté au *Committee on Acoustic Emission from Reinforced Plastics* qui est maintenant affilié à l'*American Society for Nondestructive Testing*.

Vu que la nouvelle procédure est fondée sur des résultats expérimentaux obtenus lors de ce projet, il est de mise de restreindre sont champ d'application aux contenants de PRF/ABB sous pression pour le présent. Les auteurs sont d'avis qu'elle aurait une plus grande portée, mais il est nécessaire de faire les études appropriées avant d'étendre son champ d'application.

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1.0 INTRODUCTION

This is the fifteenth and final report for the project titled "Development of Non-destructive Testing Methods for Proving and Re-testing Low Pressure, Fibre Reinforced Plastic Highway Tankers". The project was accepted as a result of an Unsolicited Proposal made by Les Transports Provost Inc. in 1985, and in which the Composite Materials Research Lab of the Department of Mechanical Engineering, Concordia University, was the research sub-contractor. The first tests were conducted in November of 1985. The last tests were conducted in February, 1989, after a three month extension of the three-year project was granted.

Three Steering Committee meetings were held: October 16, 1986, August 21, 1987, and November 24, 1988. On May 20, 1988, Dr. W. Jancewicz and Mr. J. Bouchard of the Dangerous Goods Directorate visited the facilities at Concordia University. A total of fourteen previous reports [1 to 14] were prepared and sent to members of the Committee and others in the community of fabricators and users of pressurized Fibre Reinforced Plastic (FRP) equipment. A videotape was prepared for the research team by Concordia University's Audio Visual Department. The tape is being submitted along with this report in fullfillment of the contracts entered into by all the parties.

In the present report, a brief sketch of the development of the project is given in chronological order. The differences between the first and the final draft of the Proposed Recommended Practice are

noted. The Proposed Recommended Practice (given in Annex A) is applied to all the data accumulated which has an appropriate sequence of loading cycles. Finally, remarks on the scope and limitations of the Proposed Recommended Practice are made, and suggestions are formulated for future work.

2.0 OVERVIEW OF PROJECT EVOLUTION

From the first test described in Report #1, the FRP/Balsa wood core tankers produced much higher levels of Acoustic Emission (AE) than FRP vessels without cores which the research team had tested on previous occasions. It was postulated that much of the activity was due to the core and the interfaces between core and the FRP skins. This was in part suggested by the considerable amount of activity that was produced when the tankers were unloaded to zero pressure. Since this core is not used to contain pressure in the design calculations, it was not considered to have a significant bearing on the acceptability of the tankers as far as pressure service was concerned. Furthermore, the AE activity was such that notions of Kaiser effect, Felicity effect, and Felicity ratio, which are used in some existing procedures for testing FRP vessels, were thought to be not applicable to these road tankers. The continuing AE activity during constant-pressure hold periods was also a prominent feature of the tankers. The initial pre-supposition was that the tankers which had

revealed themselves to be so noisy were of "good" quality. This was supported by the general experience of the fabricator who had used these designs for more than a decade, but was not established by any other data. The use of the **Recommended Practice for Acoustic Emission Testing of Fiberglass Reinforced Plastic Resin (RP) Tanks/Vessels** developed by the Committee on Acoustic Emission from Reinforced Plastics (CARP) would have led to the rejection of all the tankers.

Since the core-to-skin interface was thought to be the source of the difficulties, attempts were made to improve the bond. However, as the results of Report #3 showed, AE activity was not significantly reduced. The pressure containers are held on the trailers by straps. These were loosened in some tests, but no effect was observed. Also the tankers were tested with the trailer legs both down and up, but the levels of activity remained unaffected. Discussions on further attempts to improve the core and the bonding suggested that it would be either impossible to accomplish, or prohibitive in terms of cost of manufacture and weight of the tankers. Therefore, another AE testing procedure would have to be developed.

Meanwhile, measures of the attenuative properties of the tanker walls on AE stress waves were made. In empty tanks, the waves would be damped out within a radius of about 300 mm for high frequency components and about 900 mm for low frequency components. When tankers were filled with water, the stress wave paths became complicated, and no fived maximum travelling distance could be established. In some cases, this may lead to ambiguity in locating

the sources of AE. Little or no effect due to the direction of wave propagation in the tanker wall with respect to fiber orientation was detected.

During the series of tests on the second Provost tanker (S-91), the difference in behavior of a tanker allowed to recover at zero pressure for one hour and for 15 hours was recorded. This behavior was later associated with the concept of"Qualitative Felicity Ratio" first introduced in Report #6, and was a general feature of all tankers tested.

The first burst tests were conducted on an old FRP tanker with no core (tanker #7180). Report #4 suggested that both low frequency and high frequency AE activity should be considered in making acceptance/rejection decisions. The importance and usefulness of AE activity trends is first mentioned in this report. Such trends were thought to offer the possibility of eliminating or reducing difficulties due to variability in hardware/software changes, and instrumentation set-up and calibration from test to test. In the conclusion, examination of the AE activity trend during constant pressure hold periods is suggested.

In the fifth report, another method of measuring the trend by using the data collected from a sequence of several cycles is proposed. The trend of all three AE parameters (NLF, NHF, EHFHT) are shown to be very similar, indicating that they may not have to all be used in developing the new procedure. In subsequent reports, the pressurization schedule was gradually modified to better measure the

AE activity trend.

In Report #6, it is pointed out that activity does not cease after attaining a constant-pressure hold level. Rather, the activity rate decreases so that the behavior during loading and the following hold is continuous, not discontinuous. Three pressure levels (50%, 100%, and 150% of the design pressure) were proposed here, and a five minute interval between cycles is recommended. In the appendix to Report #6, the use of hot-melt adhesive to bond sensors to tankers is justified.

By the time Report #7 was written, the AE trends had become sufficiently well established to allow presentation of the first proposed pressurization schedule in Figure 7 of that report. This schedule still included a long creep-type of hold period at the upper pressure in the fourth cycle. By November 1987, after tanker S-109 was tested, the fatigue-type of schedule was chosen over the creep-type both for practical reasons and because it was thought that such a schedule would permit measurements of the AE trend more easily and unambiguously. The method of measuring the trend was also modified to a "normalized parameter" ($Z^{i,j}$).

At this point it was still planned to test only one FRP/Balsa wood core tanker to destruction. However, an old FRP tanker without core (S-33) was tested to destruction for guidance on the eventual test on a tanker with core. The results from testing this thirteen year old unit, in November 1987, were such that the project was narrowed down further. In the conclusion of Report #11, some

important aspects for consideration are mentioned: determining the generality of proposed acceptance/rejection criteria; relating behavior to margins of safety, and margins of safety to an appropriate retest interval; and demonstrating that tankers with cores behaved in a manner similar to FRP tankers without cores. It was also decided that only results from cycles up to the full test pressure should be used to accept or reject tankers. A summary of the instrumentation settings and testing procedure developed up to that time was given in this report.

The twelfth report presents tests on three tankers giving the method of measuring the AE activity trend in detail, as well as a detailed practical discussion of testing technique and data interpretation. The appropriate magnitude for the test pressure is discussed there, contrasting previous ASME requirements of 1.5 times design pressure with possible lower test pressure values. At the former levels, it is confirmed that considerable activity occurs during hold periods in creep-type cycles. A test pressure of 1.2 times design pressure was proposed, but not subsequently developed.

Up to this time, no FRP/Balsa wood core tankers had been tested to destruction. A method of testing based on evaluation of AE activity trend had been proposed. Tests on presumably "good" tankers had shown quite consistent results, and now it was necessary to see if the AE trend measurements could distinguish a "good" tanker from a "bad" tanker. A decision was reached to test several older, less expensive FRP/Balsa wood core tankers rather than one new unit. A new

small tank from another manufacturer was also included. This would improve the data base. The results of these tests to destruction are in Report #13.

A new software module was adopted during these tests. This allowed us to calculate the trend numbers on a global level (cumulated for the whole tanker) as before, but also on a local level since it can cumulate AE counts for each of the sixteen channels individually. This is the preferred method for the recommended practice envisioned since AE counts contain information on energy whereas AE events by themselves do not.

A comparison of AE trend with and without activity during hold periods showed that a difference appears as the burst pressure is approached. It was concluded that the activity during hold periods must be included in the data for the purposes of the recommended practice.

Testing of a new tanker (S-121) was conducted up to the usual pressure of 1.5 times design, i.e., 420 kPa. The sequence of cycles was selected the ascertain the effect of an intentional or unintentional pressurization up to the test pressure before the recommended sequence was conducted. The acceptance/rejection criteria must be robust enough not to falsely reject a tanker in such a situation.

From the first three burst tests on FRP/Balsa wood core tankers, it was concluded that a simple linear relation between AE trend and margin of safety could not be claimed. However, it did seem possible

to decide from the AE trend whether a tanker meets a certain minimum defined requirement for safety margin. Also, the validity of the trend numbers was restricted to certain minimum absolute levels of AE counts. Below these levels the numbers are no longer robust indicators, being too easily influenced by insignificant activity. The adoption of a second criterion to supplement the AE trend numbers was suggested. The elimination of a final creep-type cycle was once again justified for the purposes of the recommended practice.

Based on the data from all tests up to and including the test on the CPF Dualam Model tank (October 27, 1988), Draft #1 of the proposed recommended practice was presented to the steering committee on November 24, 1988. This first draft was included in Appendix 1 of Report #14.

The final tanker tests were conducted from November 1988 to February 1989, and presented in Report #14. One tanker was new and two were old. The old units were tested to destruction. The new tanker did not deviate from expected AE trends and was judged acceptable using Draft #1. Tanker #9292 did show peculiar behavior and burst at the lowest pressure yet encountered (about 280 kPa, the design pressure). In particular, results from the prescribed lead breaks during the "Instrumentation System Performance Check" on tanker #9292 contributed to a modification of the first draft.

3.0 DIFFERENCES BETWEEN DRAFT #1 AND FINAL PROPOSAL

The Proposed Recommended Practice developed during this project is based on the empirical results obtained. In the context of a Recommended Practice, it is considered appropriate not to extrapolate the results in an unwarranted fashion. This view is reflected in modifications of the title as well as the scope of the practice. Though our experience suggests that the practice should be generally applicable to fiber reinforced thermoset resin composite structures under general loads, prudence dictates that the scope be restricted until experimental evidence becomes available.

Following comments during the third meeting of the steering committee, two modifications were made to the original draft. The minimum amount of reinforcement was increased from 15% to 30% by weight. Use of the larger percentage is more in keeping with actual practice and assures sufficient reinforcement. The use of the term "operating pressure" was replaced with the term "design pressure" as defined in ASTM E1067 to avoid ambiguities. In Section 10.1, the basic value of critical count number is changed from the global value (10 000) to the local value (625). This is meant to avoid possibly penalising practitioners who use larger numbers of sensors.

Throughout the document, the word "stimulated" as in "stimulated AE" is replaced with the word "simulated".

The upper point of the useful bandwidth (Section 6.1) should be 200 kHz, not 300 kHz.

The "Instrumentation System Performance Check" of Section 8.0 now reflects the results found in testing tanker #9292 mentioned above, and presented in Report #14.

In the first draft of the practice, a tanker could be accepted in certain cases after fewer than 4 cycles at the test pressure. Review of the latest data shows that as the burst pressure is approached, curves of $Z^{i,j}$ may show an initial downward trend in the second cycle, for example, only to increase again in the third or fourth cycle. In order to reduce the resultant possibilty of incorrectly accepting a defective vessel, the final proposed practice now requires that all four cycles at the test pressure be conducted. This is reflected in the changes to Section 10.4.

A decision flow-chart is no longer included since it appears more complex than the step-by-step decision process given in Section 10.4.

4.0 APPLICATION OF FINAL PROPOSAL TO DATA

Not all the data accumulated during the project is in a form compatible with the requirements of the final proposed recommended practice. Table 1 lists all the tests performed in chronological order along with some general comments. Table 2 lists those tankers for which data is available in exactly the required form as far as cyclic loading, test pressure levels, and AE count data at both the

local and global levels is concerned. In the case of two of these units burst tests were conducted and so a margin of safety can be calculated. The calculation was done as follows:

1) identify the lowest pressure level at which the unit was rejected;
2) the next lower level is then associated with the highest pressure at which the unit would have been accepted;
3) divide this highest pressure level by 1.5 to get the highest acceptable service pressure;
4) divide the burst pressure by this highest acceptable service pressure to get the safety factor;
5) finally, the safety margin is the safety factor minus 1.0.

Results from many other tanker test, while not being in a form which can be exactly used with the proposed recommended practice, are suggestive of the consistent behavior that may be expected. This is perhaps best shown in graphic form by plots of AE trend numbers for the parameters NHF and NLF versus cycle number. Figures in Appendix B show the trend curves which have been associated with "good" tankers.

5.0 CONCLUSION

The Proposed Recommended Practice has the qualities and faults of a procedure that is empirically based. Section 4.0 above shows that it can be effective and consistent when used on real structures for which it was intended. As mentioned above, its use cannot be extended imprudently to structures beyond its defined scope. In the

context of acceptance/rejection decisions of potentially dangerous structures, it is felt that this scope must be restrictively defined.

To broaden the applicability and usefulness of the practice several questions still need to be answered with empirical evidence.

1) Can FRP pressure vessels without balsa wood cores be tested?
2) Can FRP vessels subjected to vacuum loadings be tested?
3) What is the relation between safety margin and "remaining life" of the equipment?
4) Can a better understanding of the relation between current AE activity trend and current safety margin be developed?
5) Is it possible to specify the time of the next required AE test from results of the test just completed?

Further experimental work is required to reliably answer these questions.

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13. Ibid., "Acoustic Emission Testing of Three Tanks: Provost S-37 and S-121, and C.P.F. Dualam Model Tank", Report 13, ibid., November 1988.

14. Ibid., "Acoustic Emission Testing of Three Tankers: Provost S-122, Provost #9292, and Provost S-40 (Rear Tank)", Report 14, Ibid., February 28, 1989.

TABLE 1. CHRONOLOGICAL LIST OF ALL UNITS TESTED DURING THE PROJECT

NO.	DATA	TANKER	CONDITION	TEST DURATION	REPORT NO.
1	Nov. 85	S-85	new	1 day	Provost #1
2	June 86	S-91	new	2 days	Provost #3
• 3	July 86	#7180	service 13 years (first burst test)	2 day	Provost #4
4	July 86	S-92	new	2 days	Provost #6
5	Oct. 86	S-95	new	1 day	Provost #5
6	April 87	S-92	8.5 months service (second test)	2 days	Provost #6
• 7	April 87	#7180	second burst test (after repair)	2 days	Provost #4
8	July 87	S-82	new	1 day	Provost #7
9	Sept. 87	S-104	new	2 days	Provost #9
10	Oct. 87	S-106	new	1 day	Provost #10
• 11	Oct. 87	S-33	service 13 years	1 day	Provost #11
12	Oct. 87	S-107	new	1 day	Provost #10
13	Oct. 87	S-108	new	1 day	Provost #10
14	Nov. 87	S-109	new	1 day	Provost #10
• 15	Nov. 87	S-33	burst test	1 day	Provost #11
16	Dec. 87	S-92	17 months service (third test)	1 day	Provost #12
17	March 88	S-74	service 4 years	2 days	Provost #12
18	April 88	S-113	new	2 days	Provost #12
19	Aug. 88	S-37	service 12 years (burst test)	7 days	Provost #13
20	Sept. 88	S-37	second burst test (after repair)	11 days	Provost #13
21	Sept. 88	S-121	new	2 days	Provost #13
22	Oct. 88	CPF MODEL TANK	new (burst test)	10 days	Provost #13
23	Nov. 88	S-122	new	2 days	Provost #14
24	Dec. 88	#9292	service 12 years	3 days	Provost #14
25	Dec. 88	S-40(REAR)	service 11 years	12 days	Provost #14

• FRP only (no Balsa wood core)

TABLE 2. LIST OF TANKERS AMENABLE TO EXACT APPLICATION OF FINAL PROPOSED RECOMMENDED PRACTICE.

	Container No.	Pressure	Accepted/Rejected	Comment
1.	S-37	420 kPa	Accepted	
		504 kPa	Accepted	
		588 kPa	Rejected	
		burst at 789 kPa		Safety margin = 1.3
2.	S-121	420 kPa	Accepted	new
3.	S-122	420 kPa	Accepted	new
4.	S-40 (REAR)	220 kPa	Accepted	
		280 kPa	Accepted	
		336 kPa	Accepted	
		392 kPa	Accepted	
		420 kPa	Rejected	
		burst at 756 kPa		Safety margin = 0.9

ANNEX A

RECOMMENDED PRACTICE FOR TESTING/RETESTING PRESSURIZED HIGHWAY ROAD TANKERS MADE OF FIBERGLASS REINFORCED PLASTIC WITH BALSA CORES USING ACOUSTIC EMISSION MONITORING

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1.0 SCOPE

This recommended practice applies to acceptance testing using *Acoustic Emission** (AE) monitoring of new pressure containers and in-service pressure containers made of fiberglass reinforced plastic (FRP) materials. The type of reinforcing material is restricted to glass, and the composite must contain over 30% by weight of reinforcement. The form of the reinforcing material may be mat, roving, cloth, or a combination of these. The matrix material is restricted to thermosetting polymers. The pressure container will be of sandwich construction with a balsa wood core and FRP skins. This recommended practice is not restricted to any particular technique of fabrication or method of design. The pressure container is not restricted, a priori, as to size or shape. The *design pressure* may be up to 520 kPa (absolute) above static pressure head due to contents.

This recommended practice does not specify an interval between tests to re-qualify pressure containers. Vacuum containers are not included within the present scope.

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* See Section 3 for definition of *italicized* terms.

2.0 APPLICABLE DOCUMENTS

The following documents are pertinent to this recommended practice: **ASTM E610, ASTM E650, ASTM E750, ASTM E1067,** and **Recommended Practice for Acoustic Emission Testing of Fiberglass Reinforced Plastic Resin (RP) Tanks/Vessels,** 1987 (hereafter designated as the CARP Recommended Practice, where the acronym CARP stands for Committee on Acoustic Emission from Reinforced Plastics).

3.0 TERMINOLOGY

This recommended practice incorporates, by reference, all the terminology in **ASTM E610 Standard Definitions of Terms Relating to Acoustic Emission,** and in **ASTM E1067 Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels.** Where terminology is included in neither of the above, it is defined in section 3.1 below. The first occurrence of defined terms is *italicized.*

3.1 Definitions

Test Pressure (tp): the highest pressure used in testing a given pressure container. The test pressure is 1.5 times the design pressure (see Section 9.0 below).

4.0 SIGNIFICANCE AND USE

This recommended practice does not rely principally on absolute quantities of *AE counts* or other parameters. It basically relies on the trend of AE counts detected during a fixed sequence of repeated loading cycles. It specifies acceptance/rejection criteria for pressure containers within the present scope. If a pressure container is rejected, it may be repaired and retested following the same procedure and using the same acceptance/rejection criteria.

AE can be attributed to several processes within the volume of the test structure. Some processes may indicate the presence and activity of significant unacceptable flaws (eg., growing resin cracks, fiber fracture, delaminations). Other processes may cause AE, but may be indicative of structurally insignificant material events (eg., rubbing at interfaces). The methodology adopted for this recommended practice is such that structurally insignificant AE does not interfere with the proper interpretation of the data.

Experience has shown that *zone location*, relying on which channel first records an event, is not always unambiguous in the case of tests on large structures. In cases where a pressure test is conducted, this can be due to the effect of the liquid contents on stress wave propagation, as well as to differences in AE channel characteristics. For these reasons, zone location is not used in this recommended practice.

5.0 PERSONNEL QUALIFICATION

The AE examination shall be performed by qualified personnel. Qualification shall be based on a documented program (including training) that certifies personnel capable of conducting AE examinations of FRP tanks and vessels. The documented program shall include as a minimum the following general topics:

1) basic technology of AE,
2) mechanisms of AE generation in pressure containers within the scope of the present practice,
3) AE instrumentation,
4) instrumentation check,
5) data collection and interpretation,
6) examination report.

6.0 INSTRUMENTATION

The AE instrumentation consists of sensors, signal processors, and recording equipment. (Additional information on AE instrumentation can be found in ASTM E750.) Together the above constitute *AE channels*.

As a minimum, the AE instrumentation must be able to record and display AE counts on a per-channel basis, cumulated AE counts from all channels, plus load and time on a continuous basis. A sufficient number of channels must be used to enable the detection of *sources of simulated AE* from all areas of the structure (see Section 6.1 and 8.0). All pressure must be recorded with an

accuracy of ± 2% of the test pressure.

For the purpose of this recommended practice, all amplitudes are given in dB, with the reference being 1 microvolt at the AE sensor equivalent to 0 dB. The AE instrumentation must have a signal detection threshold set to 40 ± 2 dB. Signals ranging up to 100 dB in amplitude must be recorded by the system, providing an effective dynamic range of 60 dB for the test.

The method of verifying the instrumentation in the actual testing situation is explained in Section 8.0 below.

6.1 AE Channels

AE instrumentation must respond to signals between 20 kHz and 200 kHz. The 20-200 kHz bandwidth has been found acceptable for testing in most industrial environments. If problems with extraneous noise are encountered, the use of filters to eliminate troublesome frequencies may be considered. If noise cannot be eliminated nor accounted for in the data interpretation phase, the test shall be stopped; it may be conducted after the problem is corrected.

Signals should not be censored as to "low" or "high" frequency. All signals within the instrumentation bandwidth given above are equally significant for the purpose of this test method. However, since it is known that lower frequencies are attenuated less than higher frequencies, this behavior can be used to advantage to ensure complete coverage of a test structure.

The elements of each AE channel (i.e., sensors, preamps, filters, main amplifier, etc.) should be matched in characteristics.

The number and characteristics of AE channels used must be such that simulated AE from standard lead pencil breaks (see Section 8.0) can be detected from all areas of the structure.

In locating the sensors, areas of secondary bonding such as heads, manholes, and nozzles must be given appropriate weighting. In Figure 1, a typical configuration of AE transducers is shown.

6.2 AE Sensor Sensitivity

Refer to ASTM E1067 for discussion of AE sensor sensitivity. In all cases, all sensors shall be sufficiently sensitive to permit carrying out the Instrumentation System Performance Check (section 8.0) without using gain levels that will cause extraneous electronic noise on the system.

6.3 AE Sensor Attachment

AE sensors must be coupled to the structure with an appropriate medium (eg., ultrasonic couplant, vacuum grease, adhesive). The use of hot-melt thermoplastic glue sticks applied with a glue gun has been found convenient since it does not over-attenuate signals, it can hold the sensor fixed in place for the entire test period in any position on the structure, and it allows easy and safe removal of the sensors The couplant must

be compatible with the material of the test structure, the AE sensors, and the test environment. All electrical cables must be fixed (eg., taped down) so as not to impose strain on the connectors or generate electrical noise.

7.0 TEST PREPARATIONS

All safety procedures normally required on the test site must be observed. The nature of the instrumentation and the required personnel activity related to the testing must be evaluated and judged compatible with the environment on the test site.

Precautions must be taken to safeguard personnel on site from the consequences of possible catastrophic failure. Pressure release outlets with sufficient flow capacity must be located within easy reach of the testing personnel. It is recommended that water be used as the pressure medium for pressure tests.

Pressure containers that are not tested in service shall be supported in such a manner as to simulate support conditions in service as closely as practicable, and to minimize extraneous noise.

8.0 INSTRUMENTATION SYSTEM PERFORMANCE CHECK

Once all sensors are in place, and the AE instrumentation is ready, simulated AE must be applied to the structure at a distance of 200mm from each sensor. Stimulated AE is from the breaking of 0.5mm 2H Pentel lead held in a mechanical pencil, using the holder shown in Figure 2. It may be necessary to disconnect all channels except the one being verified if more than one channel responds to the lead break. The channel response may be measured when the pressure container is filled with pressurizing medium or empty. At least 3 lead breaks on a 200mm radius circle around each sensor must be recorded. Each channel must report a minimum average AE count of 30 per lead break. If a lower average count is recorded, the combination of sensor, cable, and channel used shall be varied to determine if the problem is due to instrumentation, method of bonding of the sensor, or vessel characteristics. (A piece of material of good quality and of the same construction as the tanker wall may be used to determine the condition of the suspect components.) If the components are at fault they shall be modified. Modification may simply entail re-attaching the sensor or changing the sensor, or may involve other changes to other components of the AE channel involved. If low counts are due to the tanker wall characteristics, results of the lead break tests shall be recorded for inclusion in the report, and the procedure continued.

The above performance check must be repeated at the end of the

test and all AE channels must be found acceptable. Otherwise, the test results shall be deemed invalid, and the test shall be repeated after proper modification/verification.

9.0 TEST PROCEDURE

This recommended practice involves the loading of a pressure container according to the recommended loading schedule. During the loading, AE activity is monitored along with pressure and time. The data accumulated is used to calculate AE trend numbers when the amount of AE activity is "large"; these numbers are defined in Section 10.2 below. These numbers can be calculated as the test is in progress (i.e., the test does not require extensive post-test processing of data).

The recommended loading schedule is shown in Figure 3. Three pressure levels must be established for the test. The first is the test pressure itself. The other two pressure levels are 1/3 and 2/3 of the test pressure. The complete list for the six cycle sequence is

CYCLE #	MAXIMUM PRESSURE
1	1/3 of test pressure
2	2/3 of test pressure
3 to 6	full test pressure

It is required that the test pressure be equal to 1.5 times the design pressure. For the purpose of testing, over-pressure protection devices are temporarily rendered inoperative.

The rate of loading shall be no greater than 2% of the test pressure per minute. Although some adjustment of flow rate may be required during a test, the rate of loading should be as uniform as possible. The rate of unloading shall be no greater than 5% of the test pressure per minute, and should also be as uniform as possible.

During loading, any false AE due to water entering the container shall be minimised by adjusting the rate of loading. Lowering the rate of flow will usually lower such false activity. Noise from leaks (eg., at manholes) may be eliminated by placing rags at the points where the water impacts the surface.

The initial hold of 25 minutes is used to monitor noise from the environment. Background noise must be minimized. If background noise is shown to be constant with time during the entire test, it shall be discounted on a pro-rata basis before tabulating data. Background noise that is not shown to be constant must be noted and discounted from the data-set before tabulation. If the background noise cannot thus be discounted, the test must be stopped, and the problem corrected before the test is resumed/repeated.

All constant pressure hold periods including those at zero pressure, except the initial period before loading, shall be 5 minutes long. If for any reason another time must be used, it must

be greater than 5 minutes and the duration chosen must be the same for all such hold periods. An acceptable tolerance for the hold periods is: -0 seconds, +10 seconds.

Slight decreases in pressure during hold periods usually occur; such decrements must not be greater than 1% of the hold pressure value, or 2 kPa, whichever is greater.

In all cases, pressure containers shall be unloaded for a minimum of 15 hours before testing or re-testing. In all cases where the test pressure has been attained and, for any reason, the test sequence must be interrupted for more than 30 minutes, this minimum waiting period of 15 hours must be respected before testing is resumed/repeated.

10.0 ACCEPTANCE/REJECTION DECISION

10.1 General

AE monitoring of the pressure container must provide information on AE activity at the local level, i.e., for each AE channel individually, and at the global level, i.e., for the cumulative AE activity from all AE channels. The instrumentation system must provide this information in the form of AE counts.

The AE trend numbers are a measure of the trend of AE activity observed over repeated loading cycles. Since this recommended practice is based principally on the trend of AE activity, the

comparative magnitude of AE trend numbers from cycle to cycle can be used in the acceptance/rejection decision. Trend numbers can only be compared if they refer to the same pressure levels and hold periods. Furthermore, AE trend numbers are robust indicators of trend only when "large" numbers of AE counts are recorded. For this reason, when only "small" numbers of AE counts are recorded, another indicator comes into play. This local critical count number, n^c, is defined as 625 AE counts, and is the defined demarcation between "large" and "small" numbers of counts at the local level. Its counterpart at the global level, N^c, is simply the local value multiplied by the number of AE channels used. Thus,

$$n^c = 625 \quad ,$$

and

$$N^c = 625 \times (\text{\# of AE channels used}).$$

10.2 Definition of AE Trend Number

An AE trend number is defined as follows:

$$Z_{(s)}^{i,j} = A_{(s)}^{i,j} / A_{(s)}^{f,j}$$

where $A_{(s)}^{i,j}$ refers to AE counts in cycle "i" from the zero load level to load level "J";
in the case of results at the local level, the notation includes a subscript "s" which is the AE channel number;

J refers to the load level (J = 1 is 1/3 of test pressure, J = 2 is 2/3 of test pressure, and J = 3 is full test pressure);

f refers to the cycle number of the first cycle in which load level "J" is attained and AE activity is recorded;

i is a cycle number and takes on values "f", "f+1", "f+2", ...; values of "i" may range from 1 to 6.

Since for the first value we have $i = f$, the initial value of the AE trend numbers is, in all cases,

$$Z_{(s)}^{f,j} = A_{(s)}^{f,j} / A_{(s)}^{f,j} = 1.0 \quad .$$

Thus, all AE activity is normalized with respect to AE activity recorded on the "f^{th}" cycle. It is this normalization which is the basis for identifying the trend in AE activity. Appendix 1 gives an example of data and its treatment in the calculation of AE trend numbers.

Values of AE trend numbers shall be truncated to one decimal place before evaluating the test results.

10.3 Use of AE Trend Numbers

10.3a) All values of the AE trend numbers $Z^{i,J}$ for $J = 1/3$ and $J = 2/3$ of test pressure will be calculated (at the global level) as the data becomes available during the test. However, these values are <u>not</u> to be used in the acceptance/rejection decision-making process. The values at these two lower load levels are meant to be used to flag a possible critical situation which may develope during the first loading to the full test pressure. While attention is required at

all times, the failure of $Z^{i,j}$ to decrease monotonically with increasing values of "i", in the presence of "large" amounts of AE activity, suggests special caution while loading to the full test pressure.

10.3b) Only values of the AE trend numbers $Z_{(s)}^{i,j}$ for j = tp (i.e., full test pressure) shall be used in the acceptance/rejection decision.

10.4 Acceptance/Rejection Decision

10.4a) The AE trend numbers $Z_{(s)}^{i,tp}$ shall be calculated for both the local and the global level. The first set of values will be for cycle i = 3.

CYCLE 3:

At the global level and local levels:

IF $A^{3,tp} \leq N^c$ AND $A_s^{3,tp} \leq n^c$, for all s,

THEN GO TO CYCLE 4.

OTHERWISE, a) calculate all trend numbers $Z_{(s)}^{3,tp}$ *,

b) GO TO CYCLE 4.

* Note that all these trend numbers will be 1.0 in cycle 3.

CYCLE 4:

At the global level and local levels:

IF $A^{4,tp} \leq N^c$ AND $A_s^{4,tp} \leq n^c$, for all s,

THEN GO TO CYCLE 5.

OTHERWISE, a) calculate all trend numbers $Z_{(s)}^{4,tp}$.

GO TO CYCLE 5.

CYCLE 5:

At the global level and local levels:

IF $A^{5,tp} \leq N^c$ **AND** $A_s^{5,tp} \leq n^c$, for all s,

THEN GO TO CYCLE 6.

OTHERWISE, a) calculate all trend numbers $Z_{(s)}^{5,tp}$.

GO TO CYCLE 6.

CYCLE 6:

At the global level and local levels:

IF $A^{6,tp} \leq N^c$ **AND** $A_s^{6,tp} \leq n^c$, for all s,

THEN ACCEPT the pressure container.

OTHERWISE, a) calculate all trend numbers $Z_{(s)}^{6,tp}$.

b) **IF** $Z_{(s)}^{6,tp} \leq 0.2$ for all s,

ACCEPT the pressure container.

OTHERWISE, REJECT the pressure container.

11.0 REPORT

The report on the test shall include text describing and identifying the test structure, the test conditions, and the date of testing. The instrumentation used shall be indentified. A sketch

showing the location of the AE sensors on the structure shall be included. The "demarcation" values N^c and n^c shall be recorded. Appendix 2 shows a suggested layout. The final test results shall be tabulated as shown in Appendix 1.

12.0 BACKGROUND

This recommended practice is based on experimental work performed from 1985 to 1988 which has been the subject of several interim reports [1 to 14] and one final report [15] presented to Transport Canada. The practice is thought to fit into the the general philosophy implied in the CARP of 1987, as expressed in section 12.3, third paragraph of that document.

REFERENCES

1. Hoa, S.V., Ouellette, P., "First Acoustic Emission Test on the Provost Tanker", Report 1, Project on "Development of Non-destructive Testing Methods for Proving and Re-testing Fibre Reinforced Plastic Highway Tankers", Composite Materials Research Lab, Dept. of Mech. Eng., Concordia University, Montréal, Canada, February 1986.

2. Ouellette, P., Hoa, S.V., "Survey for the Selection of Non-Destructive Testing Techniques for Fiber Reinforced Plastic Road Tankers", Report 2, ibid., June 1986.

3. Ibid., "Second Acoustic Emission Test on Provost Tanker", Report 3, ibid., September 1986.

4. Ibid., "Acoustic Emission Test on Provost Tank 7180", Report 4, ibid., August 1987.

5. Ibid., "Acoustic Emission Test on Provost Tanker #S-95", Report 5, ibid., August 1987.

6. Ibid., "Acoustic Emission Test on Provost Tanker #S-92", Report 6, ibid., August 1987.

7. Ouellette, P., Hoa, S.V., Li, L., "Acoustic Emission Test on Provost Tanker #S-82", Report 7, ibid., August 1987.

8. Ibid., "Fiberglass Reinforced Tanker Testing Methodolgy (Acoustic Emission Applied to Composite Materials)", Report 8, ibid., August 1987.

9. Ibid., "Acoustic Emission Testing of Provost Tanker S-104 (#7990)", Report 9, ibid., January 27, 1988.

10. Ibid., "Acoustic Emission Testing of Provost Tankers S-106, S-107, S-108, and S-109", Report 10, ibid., March 11, 1988.

11. Ibid., "Acoustic Emission Testing of Provost FRP Tanker S-33 (#7349)", Report 11, ibid., April 20, 1988.

12. Ibid., "Acoustic Emission Testing of Provost Tankers S-82, S-74, and S-113", Report 12, ibid., May 20, 1988.

13. Ibid., "Acoustic Emission Testing of Three Tanks: Provost S-37 and S-121, and C.P.F. Dualam Model Tank", Report 13, ibid., November 1988.

14. Ibid., "Acoustic Emission Testing of Three Tankers: Provost S-122, Provost #9292, and Provost S-40 (Rear Tank)", Report 14, ibid., February 28, 1989.

15. Ibid., "Final Report (No. 15) Development of Non-destructive Testing Methods for Proving and Re-testing Low Pressure, Fibre Reinforced Plastic Highway Tankers", Report 15, ibid., February 28, 1989.

- LF---LOW FREQUENCY SENSOR
- HF---HIGH FREQUENCY SENSOR

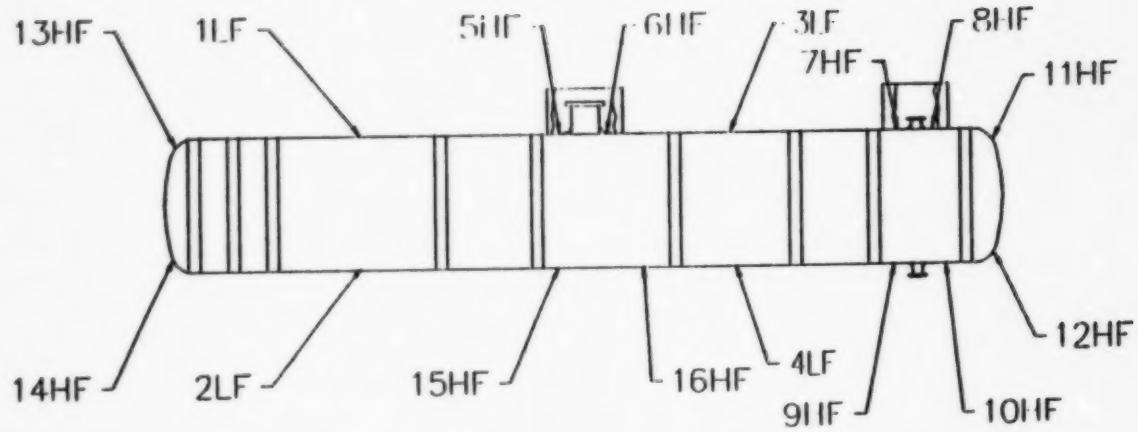

FIGURE 1. TYPICAL TEST CONFIGURATION SHOWING AE SENSOR LOCATION ON A ROAD TANKER.

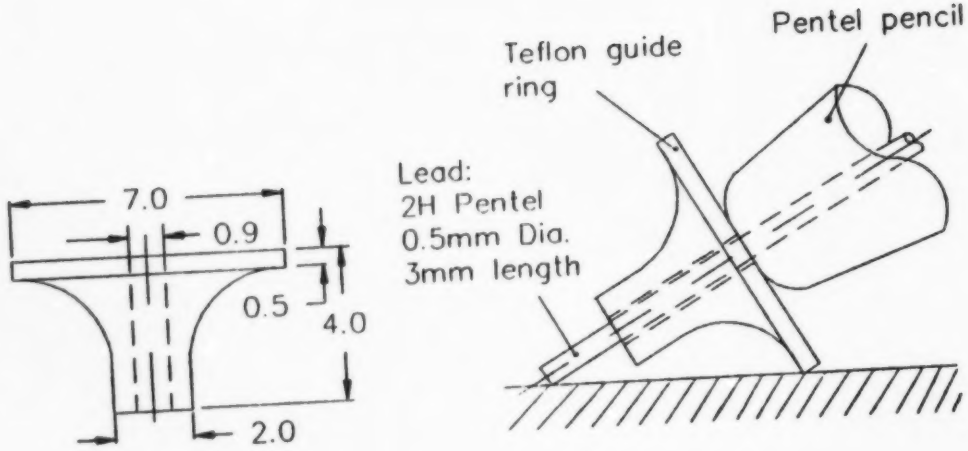

FIGURE 2. SKETCH OF TEFLON HOLDER USED IN PRODUCING SIMULATED AE BY BREAKING 0.5MM 2H PENTEL PENCIL LEADS, ADOPTED BY THE EUROPEAN WORKING GROUP ON ACOUSTIC EMISSION (EWGAE) [IN NDT INTERNATIONAL, AUGUST 1981, p. 184].

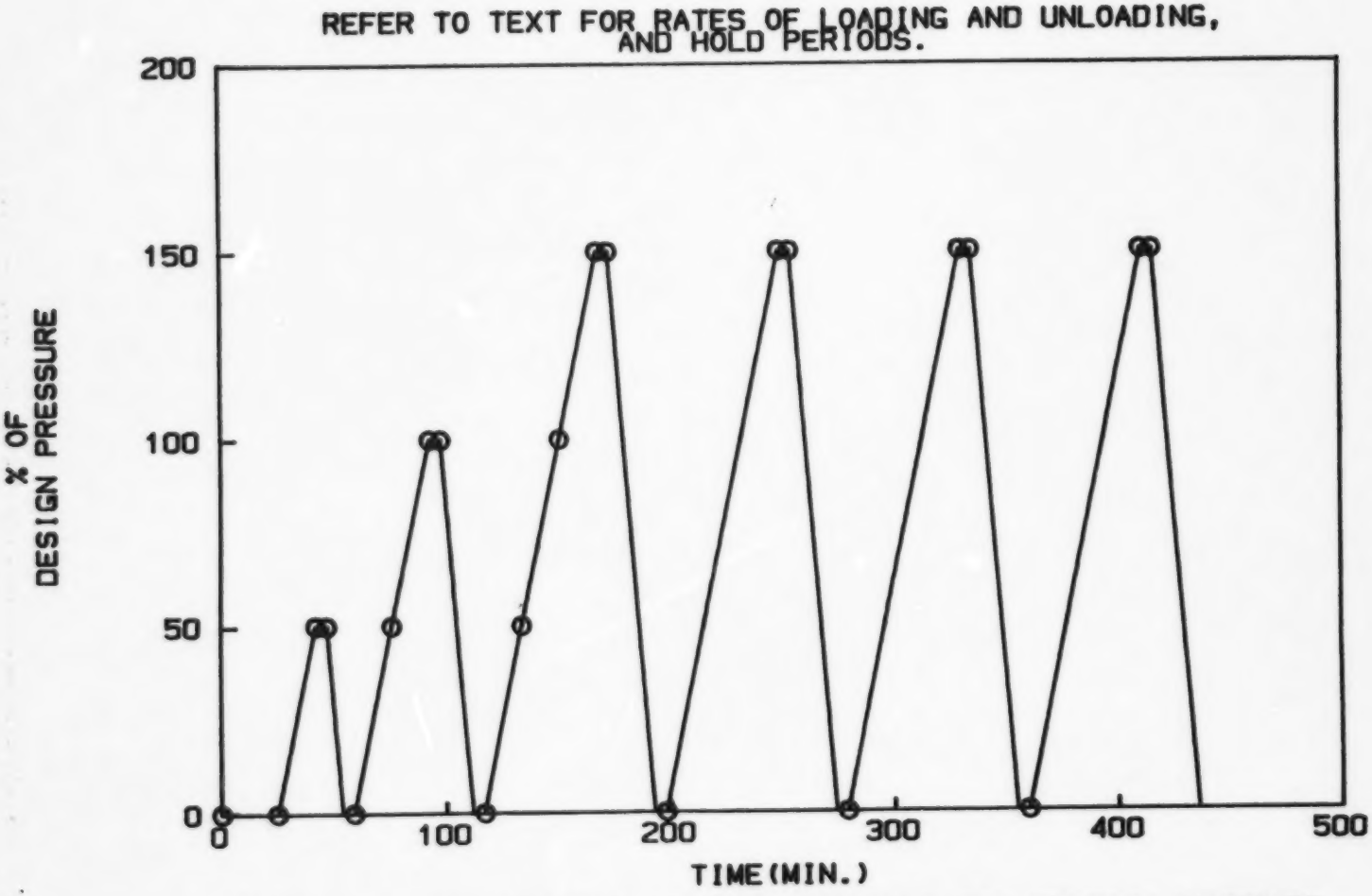

FIGURE 3. RECOMMENDED LOADING SCHEDULE FOR TESTING PRESSURE CONTAINERS USING AE MONITORING. SYMBOLS INDICATE POINTS AT WHICH DATA MUST BE RECORDED.

APPENDIX 1

Full data-set including AE trend numbers in a typical test for cycles 3 to 6 at the test pressure level. All data include AE activity during hold periods.

CH.	CYCLE #3		CYCLE #4		CYCLE #5		CYCLE #6	
#	ΣNLT	Z	ΣNLT	Z	ΣNLT	Z	ΣNLT	Z
1	38 990	1.00	2 345	0.06	609	0.02	250	0.01
2	24 510	1.00	3 090	0.13	346	0.01	705	0.03
3	56 600	1.00	3 604	0.06	411	0.01	1 236	0.02
4	13 668	1.00	851	0.06	303	0.02	298	0.02
5	37 015	1.00	4 035	0.11	663	0.02	360	0.01
6	25 670	1.00	5 202	0.20	1 114	0.04	582	0.02
7	37 396	1.00	2 004	0.05	889	0.02	257	0.01
8	19 705	1.00	2 616	0.13	702	0.04	607	0.04
9	17 947	1.00	2 208	0.12	1 136	0.06	379	0.02
10	71 558	1.00	2 921	0.04	495	0.01	395	0.01
11	8 597	1.00	1 117	0.13	154	0.02	119	0.01
12	42 995	1.00	2 680	0.06	657	0.02	200	0.01
13	2 558	1.00	192	0.08	133	0.05	32	0.01
14	6 277	1.00	505	0.08	198	0.03	119	0.02
15	4 403	1.00	210	0.05	37	0.01	64	0.02
16	12 101	1.00	932	0.08	78	0.01	86	0.01
Σ *	419 990	1.00	34 512	0.08	7 925	0.02	5 779	0.01

* This is the AE activity summed over all the 16 channels used.

AE trend numbers must be truncated to one decimal place before evaluating the results.

APPENDIX 2

TEST STRUCTURE: _____

OPERATING PRESSURE: _____

TEST PRESSURE: _____

ORIGINAL TEST DATE: _____

CURRENT TEST DATE: _____

TEST FLUID (@ TEMPERATURE): _____

AMBIENT TEMPERATURE: _____

_____

INSTRUMENTATION : _____

_____

CHANNEL #						...
SENSOR #						...

TRANSDUCER LOCATIONS: See sketch included

_____

TEST PROCEDURE: _____

n^c = 625 , N^c = ...

TEST CONCLUSION _____

TEST PERSONNEL: _____

ANNEX B

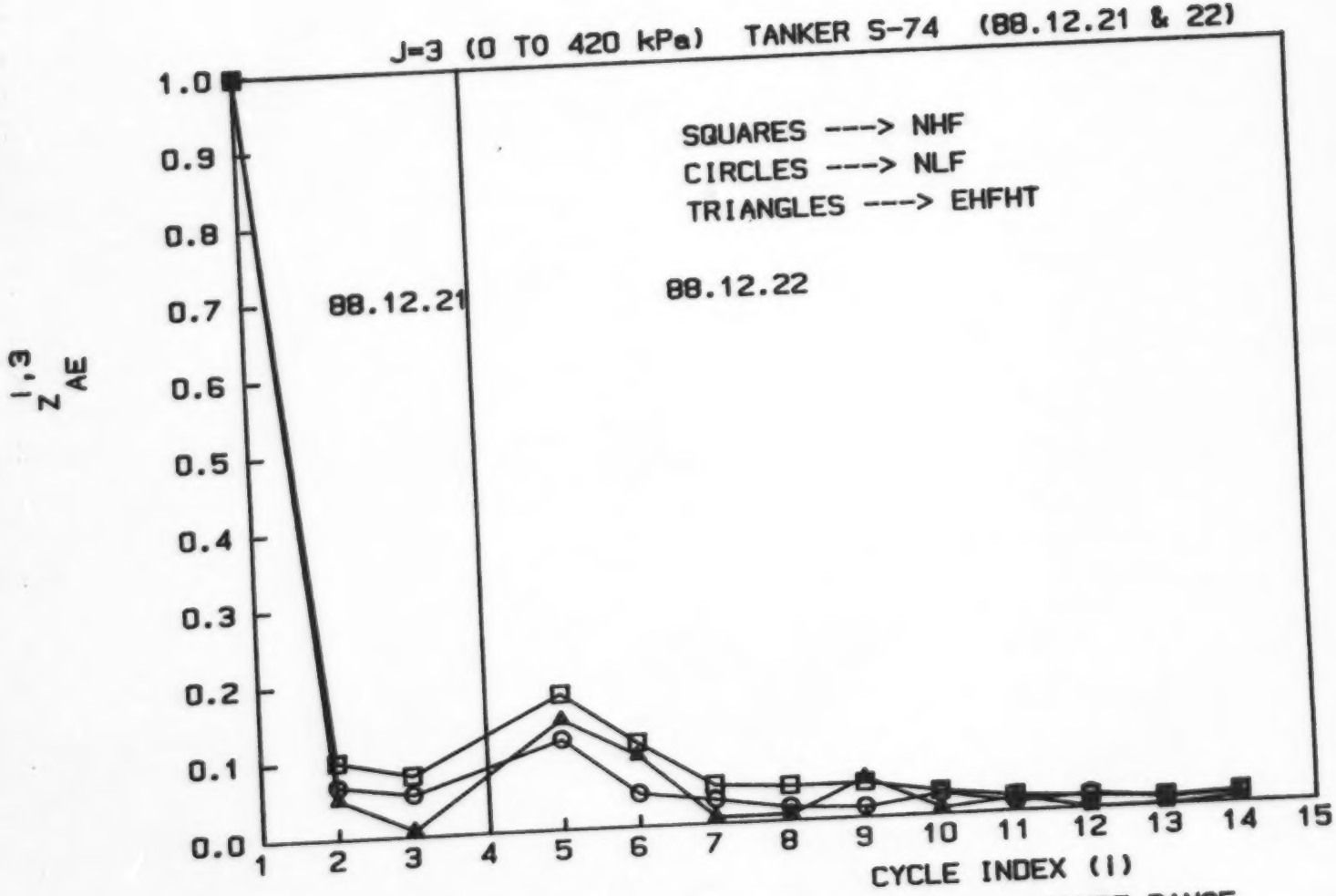

FIGURE 10. PARAMETER Z FOR THE THIRD PRESSURE RANGE. FROM REPORT NO. 12.

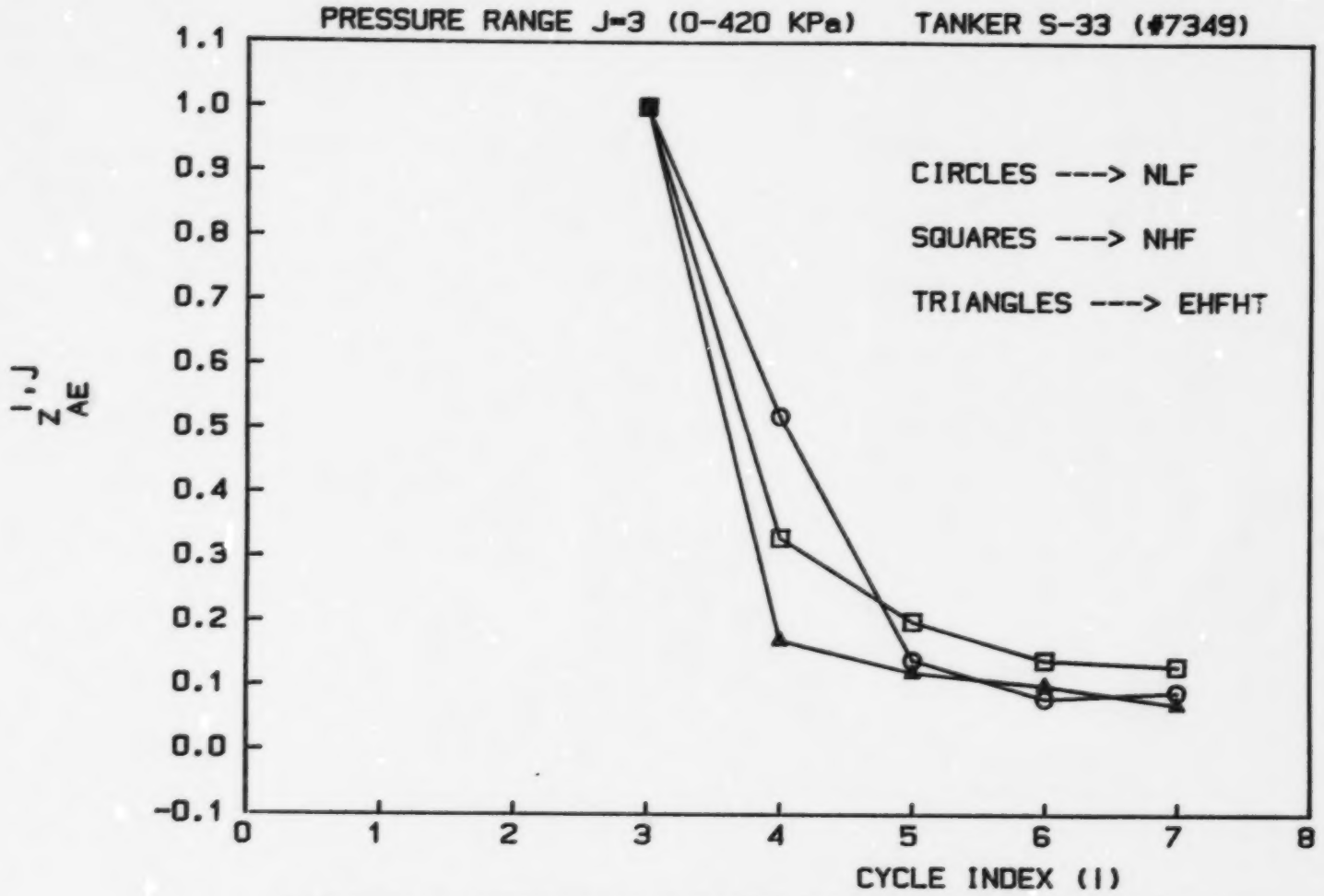

FIGURE 6C. PARAMETER Z BASED ON FIRST DAY OF TEST ONLY, FROM REPORT NO. 11.

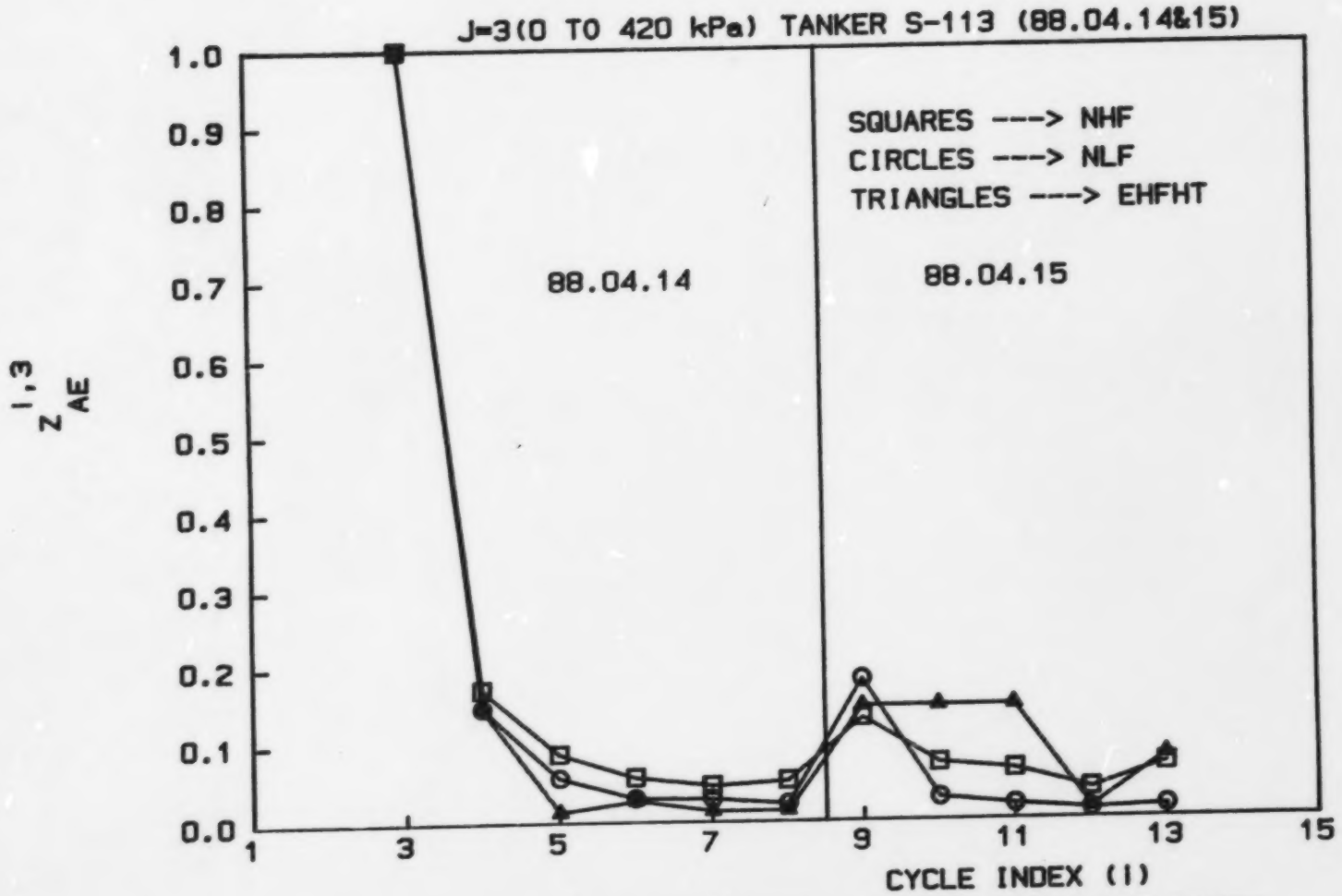

FIGURE 17. AE PARAMETER Z FOR THE THIRD PRESSURE RANGE. FROM REPORT NO. 12.

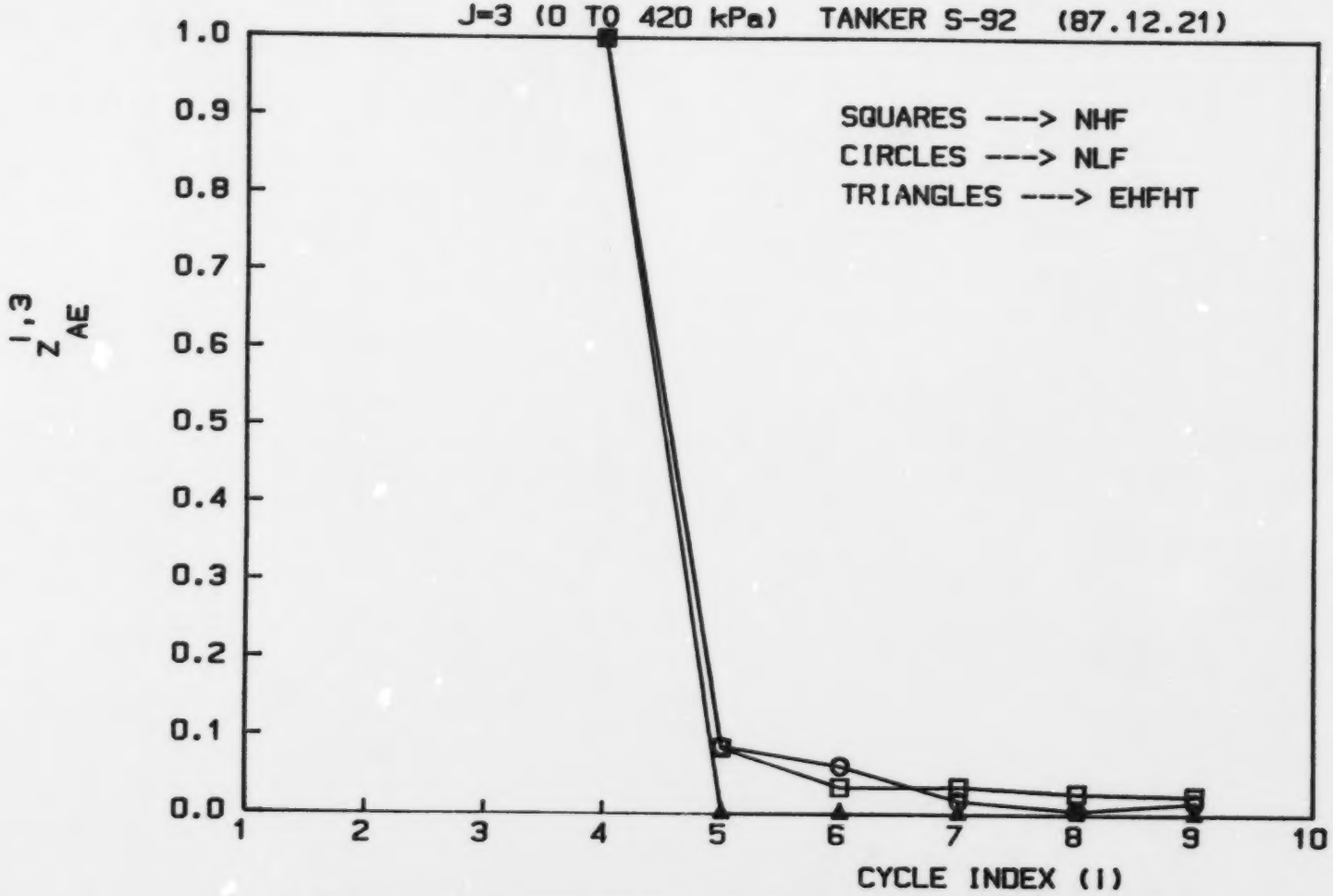

FIGURE 5C. PARAMETER Z FOR THE THIRD PRESSURE RANGE.
FROM REPORT NO. 12.